Parametric study to extract bridge frequencies from the dynamic response of passing vehicles

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ABSTRACT

A conventional way to identify bridge frequencies is utilizing vibration data measured directly from the bridge. A drawback with this approach is that the deployment and maintenance of the vibration sensors are generally costly and time-consuming. One way to cope with the drawback is an indirect approach utilizing vehicle vibrations while the vehicle passes over the bridge. In the indirect approach, however, the vehicle vibration includes the effect of road surface roughness, which makes it difficult to extract the bridge modal properties. One solution may be subtracting signals of two trailers towed by a vehicle to reduce the effect of road surface roughness. A simplified vehicle-bridge interaction model is used in the numerical simulation; the vehicle - trailer and bridge system are modeled as a coupled model. In addition, a laboratory experiment is carried out to verify results of the simulation and examine feasibility of the damage detection by the indirect method.

1 INTRODUCTION

Monitoring aged and deteriorated structures including bridges has been an important technical issue in many countries. For bridge structures, structural health monitoring based on vibration data has become a more popular tool for the condition assessment of bridges. A conventional way to identify bridge frequencies is utilizing vibration data measured directly from the bridge, using vibration sensors mounted on the bridge. A drawback with this approach is that the deployment and maintenance of the vibration sensors are generally costly and time-consuming. One way to cope with the drawback with the conventional approach is an indirect approach [1].

The feasibility of extracting bridge dynamic parameters such as natural frequency from the dynamic response of an instrumented vehicle has been verified theoretically. The feasibility of this method in practice was examined experimentally by passing an instrumented vehicle over a highway bridge in Taiwan [2]. Feasibility of the indirect method is also investigated by means of laboratory moving vehicle experiment on a model bridge, and concluded importance of removing roadway roughness to improve identifiability [3, 4]. Two approaches can be considered to resolve such a problem. One approach is to increase the vibration amplitude or energy of the bridge by allowing the bridge to be exposed to existing traffic or accompanying vehicles. The other approach is to reduce or eliminate the effect of road surface roughness. To eliminate or reduce the effect of road surface roughness by first synchronizing the response of the two vehicles with respect to the same contact points, and then by subtracting the synchronized response of one vehicle from the other.

In this study, a numerical simulation is carried out to investigate the effect of vehicle speed and trailer properties on the performance of the indirect method. A simplified vehicle-bridge interaction model is used in the numerical simulation; the vehicle-trailer and bridge system are modeled as a coupled model that allows for multiple vehicles crossing the bridge. In addition, a laboratory experiment is carried out to verify results of the simulation and examine feasibility of damage detection by mean of the indirect method.

2 EXTRACTION OF BRIDGE NATURAL FREQUENCY FROM TWO TRAILERS

The vehicle response contains not only dynamic characteristics of the bridge and vehicle but also other information such as the driving-related frequencies and road surface effects, which makes the extraction of bridge frequencies difficult. In order to eliminate those effects, this study has proposed a method using a tractor and two following trailers. The tractor plays a role as an exciter of the bridge vibration and the two trailers play roles as response receivers analogous to moving sensors. If the two trailers are identical, their responses are closely correlated but with a time difference. Therefore, the response of one trailer subtracted by the response of the other at the same point may eliminate the effect of road surface roughness.

3 ANALYTICAL AND EXPERIMENTAL INVESTIGATIONS

A vehicle-bridge interaction (VBI) was simulated utilizing a two-degree-of-freedom half-car model crossing over a finite element (FE) beam at constant speed [5].

A scaled moving vehicle laboratory experiment is performed to investigate feasibility of the indirect approach. The experiment setup and roadway profiles considered in the experiment are shown in Figure 1 in which three simple beams for accelerating, decelerating and observation are used. Roadway profiles were considered in the experiment as exist on actual bridges. The scaled bridge model used in the experiment is a 5.4 m simply supported steel beam. It is fitted with accelerometers at quarter span, mid-span and three-quarter span to monitor its response in free vibration tests and during crossings of the vehicle over the bridge. The beam properties obtained from the manufacturer and free vibration tests are given in Table 1

The vehicle model is used for measurement is three vehicles consisting of a tractor and two following trailers, as shown in Figure 1. The tractor is a two-axle vehicle, which serves to excite the bridge into motion and play the role of an exciter to the bridge. It also includes a wireless router and data-logger which allows the acceleration data to be recorded remotely. The trailer is a two-axle vehicle, which will be excited by the bridge that is already in vibration and serve as a receiver of the bridge motions. It is fitted with two accelerometers to monitor the vehicle bounce motion; these are located at the centre of the front and rear axles respectively. The two trailers have identical properties. The model trailers were adjusted to obtain the same axle configuration and dynamic response. The property of the tractor and trailers model is given in Table 2.

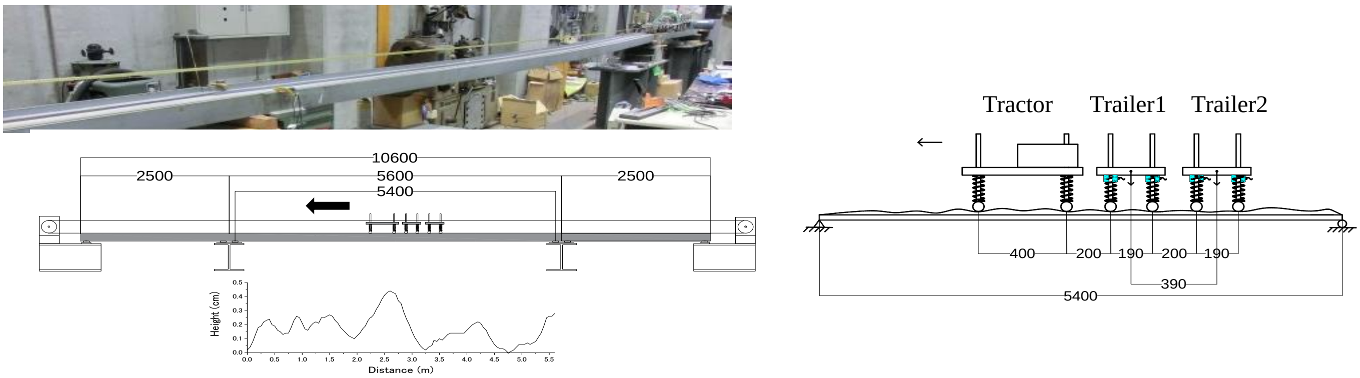


Figure 1 Experimental setup

Table1 Bridge modal properties

Span length (m)	Material density (kg/m^3)	Cross sectional area (m^2)	Natural frequency (Hz)	
			first	second
5.4	7800	6.9×10^{-3}	3.03	12.1

Table2 Vehicle properties

Vehicle	Mass (kg)		Suspension stiffness (N/m)		Damping constant		Natural frequency (Hz)	
	Axle1	Axle2	Axle1	Axle2	Axle1	Axle2	Axle1	Axle2
Tractor	7.9	13.4	2680	4570	0.055	0.056	2.93	2.93
Trailer (T1)	6.7	6.7	719	719	0.084	0.084	2.33	2.33
Trailer (T2)	6.7	6.7	830	830	0.077	0.077	2.51	2.51

Two different trailer models, of which the natural frequency of the bounce motion can be varied using different springs, are considered in the experiment. The two trailers, called T1 and T2 are used in experiment. Natural frequencies for the bounce motion of two trailer models are 2.33Hz and 2.51Hz respectively. The speed of the vehicle was maintained constant by an electronic controller as it crossed the bridge. The entry and exit of the vehicle to the beam was monitored using laser sensors. Three different scaled vehicle speeds of S1 =0.46 m/s and S2 = 0.93 m/s are considered in order to investigate the effect of the vehicle speed. Therefore, four traffic scenarios are considered: SCN1 of T1 trailers travelling with speed of S1; SCN2 of T1 trailers travelling with speed of S2; SCN3 of T2 trailers travelling with speed of S1; SCN4 of T2 trailers travelling with speed of S2.

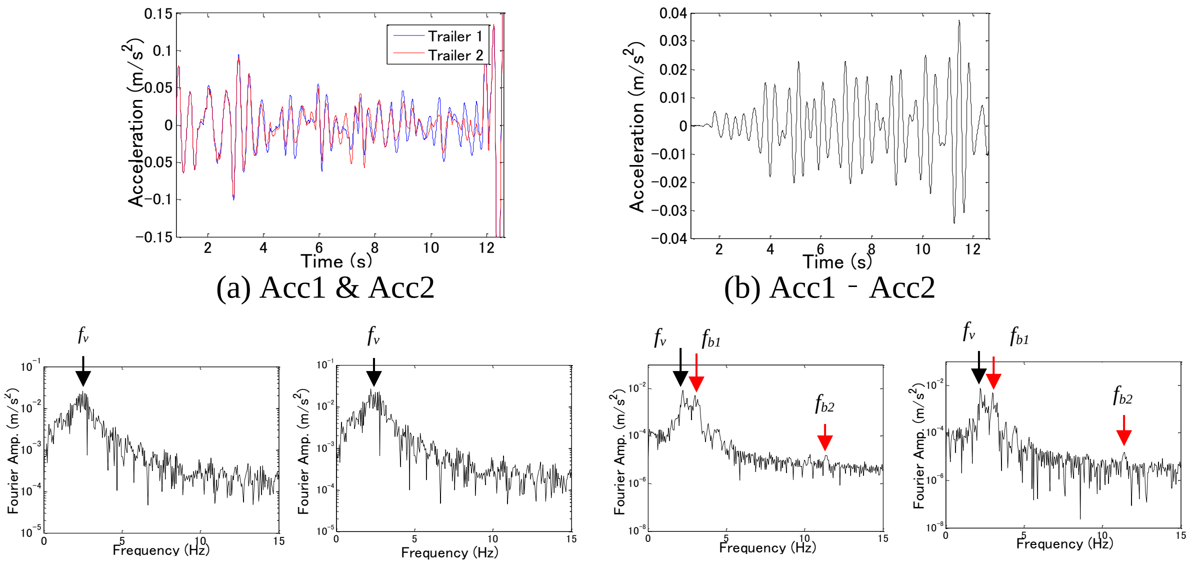
4 RESULTS

4.1 Numerical simulation

The aim of the simulation is to investigate the effect of vehicle speed, trailer properties on the performance of the indirect method. A simplified vehicle-bridge interaction model is used in the numerical simulation; the vehicle-trailer and bridge system are modeled as a coupled model that allows for multiple vehicles crossing the bridge. The results of numerical simulation are shown in Figures 2, 3 and 4 in which “Acc1” indicates acceleration of Trailer 1 and “Acc2” indicates acceleration of trailer2, and “Acc1-Acc2” denotes subtracting Acc2 from Acc1. Moreover FFT[.] indicates the fast Fourier transform of a signal.

Figure 2(a) shows accelerations measured at the T1 and T2 trailers, and the residual by subtracting the acceleration of T2 from T1, ie. Acc1-Acc2, is shown in Figure 2(b). Fourier spectra of Acc1 and Acc2 are shown in Figures 2(c) and (d). Figure 2(e) shows Fourier spectra of the residual response, namely FFT(Acc1-Acc2) and Figure 2(f) shows the residual spectra from the other, namely FFT(Acc1)-FFT(Acc2). It is observed that the frequencies similar to bridge natural frequencies are identified as shown in Figures 2(e) and (f). Moreover the subtracted response of two trailers (FFT[Acc1-Acc2]) show clearer bridge frequencies than that from the response of a single trailer. The subtracted spectrum of the two trailers (FFT[Acc1]- FFT[Acc2]) also showed clear bridge frequency.

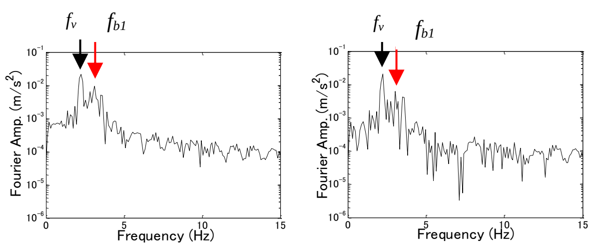
To investigate the effect of vehicle speed and dynamic properties of trailers to the identifiability, three scenarios of vehicle speed are considered, i.e. SCN1, SCN2 and SCN3. The SCN2 (T1-S1) (see Figure 2(e) and (f)) led to more clear bridge frequency than SCN1 (T1-S2). Comparing SCN1 and SCN3 to investigate influence of dynamic properties of trailers to the identifiability led to no obvious difference. Thus it would be concluded that lower speed may provide higher probability to detect bridge frequency.



(a) Acc1 & Acc2　　(b) Acc1 – Acc2

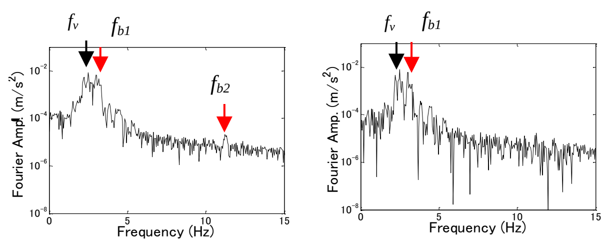
(c) FFT[Acc1]　　(d) FFT[Acc2]　　(e) FFT[Acc1-Acc2]　　(f) FFT[Acc1]-FFT[Acc2]

Figure 2 Acceleration response and Fourier spectra [SCN1: T1-S1]



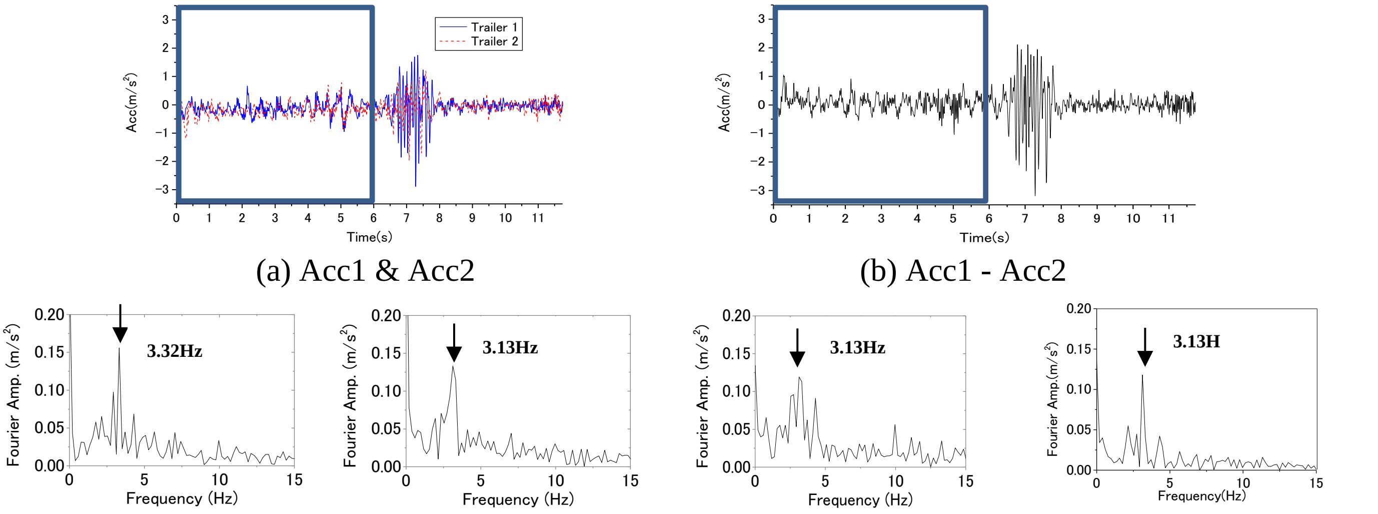
(a) FFT[Acc1-Acc2]　　(b) FFT[Acc1]-FFT[Acc2]

Figure 3 Fourier spectra [SCN2: T1-S2]



(a) FFT[Acc1-Acc2]　　(b) FFT[Acc1]-FFT[Acc2]

Figure 4 Fourier spectra [SCN3: T2-S1]



(a) Acc1 & Acc2 (b) Acc1 - Acc2

(c) FFT[Acc1] (d) FFT[Acc2] (e) FFT[Acc1-Acc2] (f) FFT[Acc1] - FFT[Acc2]

Figure 5 Acceleration response and Fourier spectra [SCN1: T1-S1]

4.2 Experimental results

The example of the experiment result is shown in Figure 5. In Figure 5(a),(b), the impulsive responses between 6 and 8 seconds caused by a big gap on the rail was not removed successfully and trailer's dynamic properties were so dominant to weaken the bridge's frequency. Thus acceleration between 0 and 6 seconds were examned in this study. Fourier spectra of the acceleration between 0 and 6 seconds are shown in Figure 5(c)-(f). Therein a dominant frequency around 3.13Hz, which is similar to the 1st bridge natural frequency (3.03Hz), was observed from FFT[Acc1] and FFT[Acc2] as shown in Figure 5(c) and (d). However, FFT[Acc1-Acc2] (see Figure 5(e)) does not show improved results while FFT[Acc1]-FFT[Acc2] (see Figure 5(f)) led to much more clear peak near 3.13Hz unlike the numerical simulation since it is difficult to synchronize the two trailers' phase in time domain.

5 CONCLUSION

In the numerical simulation, the method to eliminate the effect of road surface roughness was effective. In addition, the subtracted responses of two trailers show clearer bridge frequencies than that from the response of a single trailer or the subtracted spectrum of the two trailers. In the experiment, however, difference of Fourier spectra (ie. FFT[Acc1]-FFT[Acc2]) led to better bridge frequency identifiability than the Fourier spectrum from subtracted signal unlike the numerical simulation since it is difficult to synchronize the two trailers' phase in time domain.

The results of the parametric study indicate that vehicle speed should be lower. It is needed to consider not only vehicle speed and trailer's spring constant, but also the other parameters such as road surface roughness and examine the optimum parameters to easily extract bridge natural frequencies.

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